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Effect of supranutritional and organically bound selenium on performance, carcass characteristics, and selenium distribution in finishing beef steers[1]

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ABSTRACT: Dietary selenium influences the Se content in edible muscle of beef cattle. Limited data are available to describe the effects that feeds naturally high in Se have on production, carcass characteristics, and Se distribution in terminal tissues. Therefore, 43 crossbred steers (BW = 351 ± 24 kg) were stratified by BW and assigned to one of four dietary treatments: Se adequate (CON; n = 12), Se provided as high-Se wheat (WHT; n = 9), high-Se hay (HAY; n = 11), or sodium selenate (SEO; n = 11). Daily selenium intake for WHT, HAY, and SEO diets was 65 μg/kg BW, whereas it was 9.5 μg/kg BW for CON. Diets were similar in ingredient composition (25% wheat, 39% corn, 25% grass hay, 5% desugared molasses, and 6% wheat middling-based supplement; DM basis), isonitrogenous and isocaloric (14.0% CP, 2.12 Mcal NE_m/kg DM and 1.26 Mcal NE_g/kg DM), and offered once daily (1500) individually to steers in a Calan gate system for 126 d. At the end of the trial, steers were slaughtered; carcass data were recorded; and samples of the liver, kidney, spleen, semitendinosus, and hair were collected for Se analysis. Intake of DM, G:F, and ADG did not differ ($P > 0.13$). No differences ($P > 0.12$) were noted for hot carcass weight, organ weights, longissimus muscle area, backfat thickness, marbling scores, or quality and yield grade. Kidney, pelvic, and heart fat tended to be higher ($P = 0.06$) in CON and WHT compared with SEO and HAY steers (2.9, 2.4, 2.5, 2.9 ± 0.2% for CON, SEO, HAY, and WHT, respectively). Selenium concentrations in all tissues collected differed ($P < 0.003$) due to treatment. Distribution of Se to the kidney, spleen, and hair were similar with CON < SEO < HAY < WHT (8.40, 10.05, 10.86, 12.89 ± 0.26 ppm for kidney; 2.00, 2.60, 3.82, 5.16 ± 0.09 ppm for spleen; 1.80, 4.00, 5.93, 10.54 ± 0.56 ppm for hair; $P < 0.01$). The distribution of Se in liver and muscle (DM basis) differed from that in other tissues, with CON < HAY < SEO = WHT (2.33, 6.56, 9.91, 10.79 ± 0.80 ppm; $P < 0.01$) and CON = SEO < HAY < WHT (1.33, 1.55, 3.32, 4.41 ± 0.18 ppm; $P < 0.01$), respectively. When providing dietary Se at supranutritional levels, source of Se did not affect production or carcass characteristics, but it altered the distribution and concentration of Se throughout the tissues of finishing beef steers.

Key Words: Carcass, Distribution, Performance, Selenium, Steers

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Introduction

Supranutritional levels (three to four times the recommended amounts) of selenium have been associated with decreases in tumor occurrence in carcinogenically challenged rats (Finley et al., 2000; Whanger et al., 2000). Furthermore, daily intake of 200 μg of Se per day for 10 yr has been associated with decreased incidences of tumors in humans (Clark et al., 1996). Beef and wheat grain are the single greatest contributors of Se in North American diets (Schubert et al., 1987; Holden et al., 1991; Hintze et al., 2001). The form of Se found in beef is highly bioavailable (Shi and Spallholz, 1994). Beef from geographic regions where soil and plants contain high amounts of Se has greater muscle Se content than the beef from low-Se regions (Hintze et al., 2001). Selenium fortification of ruminant diets is restricted to less than 0.3 ppm (DM basis) and can only be supplemented as either sodium selenate or selenite (FDA, 2003). However, use of naturally high-selenium feeds is not regulated and can be used to elevate dietary selenium. Data describing the distribution of Se in young growing beef steers fed supranutritional (five- to tenfold; NRC, 1996) Se from natural, organically bound sources are limiting. We hypothesized that

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Table 1. Composition of treatment diets, and corresponding Se concentration, fed to steers (126 d at 2.38% BW, DM basis) containing either adequate (CON) Se or high Se provided in the form of sodium selenate (SEO), alfalfa/grass hay (HAY), or wheat (WHT)[a,b]

Ingredient	Feedstuff Se concentration, ppm	Treatment diet composition, %			
		CON	SEO[c]	HAY	WHT
Corn[d]	0.28	39	39	39	39
Alfalfa/grass hay (adequate Se)	0.51	25	25	—	25
Alfalfa/grass hay (high Se)	10.17	—	—	25	—
Wheat (adequate Se)[d]	0.35	25	25	25	—
Wheat (high Se)[d]	10.26	—	—	—	25
Supplement[e]	0.84	6	6	6	6
Desugared beet molasses	0.14	5	5	5	5
Diet Se concentration, ppm	—	0.38	2.84	2.80	2.86
Se intake, $\mu g \cdot kg\ BW^{-1} \cdot d^{-1}$	—	9.08	67.59	66.56	68.05

[a]Expressed on a DM basis.
[b]Isonitrogenous and isocaloric (14.0% CP, 2.12 Mcal NE_m/kg DM and 1.26 Mcal NEg/kg DM).
[c]Sodium selenate solution was suspended in desugared beet molasses and applied as a top-dressing.
[d]Corn and wheat were coarse dry-rolled.
[e]Supplement (DM basis) consisted of wheat midds (56.5%), corn (15.4%), limestone (12.4%), urea (9.2%), salt (3.4%), KCl (1.9%), Dairy VT-M (0.22%; Trouw Nutrition, Highland, IL), Rumensin 80 (0.28%; Elanco Animal Health, Indianapolis, IN), Tylan 40 (0.21%; Elanco Animal Health), vitamin E (0.11%; 44,200 IU/kg), vitamin A and D (0.11%).

dietary Se concentration and source would affect Se distribution in tissues of finishing beef steers. Therefore, our objective was to determine the effects of supranutritional dietary Se, provided in the form of high-Se wheat, high-Se alfalfa/grass hay, or sodium selenate, on production, carcass characteristics, and Se distribution and concentration in tissues of finishing beef steers.

Materials and Methods

Forty-three crossbred beef steers (351 ± 24 kg initial weight) received Ralgro implants (36 mg of zeranol; Schering-Plough Animal Health, Union, NJ) and were trained to utilize Calan gate individual feeders (American Calan, Inc., Northwood, NH) over a 28-d training period. The North Dakota State University Institutional Animal Care and Use Committee reviewed and approved animal care and use protocols used during this study. During the training period, steers consumed a common diet (Table 1) of 75% concentrate and 25% roughage (DM basis) fed at 2.38% of BW (DM basis). Feeds used in the adaptation period were purchased from regions of adequate Se concentration. Steers were stratified by BW and assigned to one of four Se treatments: adequate Se (control; 0.38 ppm; n = 11), high Se provided as high-Se wheat (2.86 ppm; n = 9), high-Se hay (2.80 ppm; n = 11), or sodium selenate supplement (2.84 ppm; n = 12). Diets (Table 1) were formulated to be isonitrogenous and isocaloric (14.0% CP, 2.12 Mcal NE_m/kg DM and 1.26 Mcal NE_g/kg DM) and fed once daily at 1500 at 2.38% of BW (DM basis). Adequate Se feed ingredients for high-Se hay and wheat treatments (Table 1) were replaced with high-Se wheat and alfalfa/grass hay (10.26 and 10.17 ppm Se, respectively) obtained from a producer near Pierre, SD, to deliver the Se treatment. For sodium selenate treatment, sodium selenate was dissolved in distilled water, suspended in desugared molasses (6 g of $NaSO_4$, 400 mL of distilled water, 200 mL of desugared molasses), and provided daily as a liquid top-dressing.

Throughout the 126-d trial, intake was monitored daily and body weight was assessed, before feeding, every 21 d. Steers were removed from feed and water, body weight was determined, and a hair sample (rump) was collected 24 h before slaughter. During slaughter (USDA-inspected facility), liver, kidneys, and spleen were collected and weighed. Duplicate 3-g samples (wet basis) of semitendinosus muscle, liver, kidney, and spleen tissues were collected, wrapped in foil, snap-frozen in liquid nitrogen, and stored below −20°C. Before digestion for Se analysis (Finley et al., 1996), hair samples were washed with acetone and distilled water (van Ryssen et al., 1989) and tissue samples were lyophilized (Genesis Model 25 LE; Virtis Co., Gardiner, NY). Hydride generation atomic absorption spectroscopy (5100 AAS; Perkin-Elmer Inc., Boston, MA) was used for Se analysis. Carcass characteristics (longissimus muscle area, backfat thickness, KPH fat, marbling scores, and quality grades) were collected 48 h postmortem. Yield grades (**YG**) were calculated based on the obtained measurements. Data were subjected to one-way analysis of variance as a completely randomized design using the GLM procedures of SAS (Version 8.0; SAS Inst. Inc., Cary, NC). Planned pairwise comparisons (least significant difference) were used to separate treatment least squares means when the *F*-test was significant ($P < 0.05$).

Results

Neither Se source nor dietary Se concentration affected performance measures (ADG, G:F, and DMI; *P*

Table 2. Performance and carcass characteristics of finishing steers fed diets (126 d at 2.38% BW, DM basis) containing either adequate (CON) Se, or high Se provided in the form of sodium selenate (SEO), alfalfa/grass hay (HAY), or wheat (WHT)

Item	Treatment				SE	*P*-value[a]
	CON	SEO	HAY	WHT		
Final BW, kg	563	572	557	567	11	0.76
Intake, kg/d (DM)	12.11	12.19	11.36	12.17	0.31	0.13
ADG, kg	1.62	1.66	1.58	1.61	0.05	0.53
G:F	0.148	0.152	0.151	0.144	0.003	0.24
Hot carcass weight, kg	339	339	331	339	7	0.82
LM area, cm^2	75.6	76.0	78.4	75.7	2.7	0.87
Backfat thickness, cm	1.0	0.9	0.9	1.2	0.1	0.12
KPH fat, %[b]	2.9[f]	2.4[g]	2.5[g]	2.9[f]	0.2	0.06
Marbling score[c]	541	555	565	610	25	0.23
Quality grade[d]	10.1	10.1	10.1	10.8	0.3	0.19
Yield grade[e]	3.2	2.9	2.8	3.3	0.2	0.20

[a]All pairwise comparisons (least significant difference; significant if $P < 0.05$). Number of steers associated with treatments were CON, n = 11; SEO, n = 12; HAY, n = 11; and WHT, n = 9.

[b]Kidney, pelvic, and heart fat.

[c]400 = Small^{00}; 500 = Modest^{00}; 600 = Moderate^{00}; 700 = Slightly abundant^{00}; and 800 = moderately abundant^{00}.

[d]9 = Select; 10 = Choice$^-$; 11 = Choice^0; 12 = Choice$^+$; 13 = Prime$^-$; 14 = Pprime^0; 15 = Prime$^+$.

[e]Percentage of boneless primal cuts: rib, loin, chuck, and round, where 1 contains the most lean tissue and is more desirable.

[f,g]Means within a row with different superscripts differ.

> 0.13; Table 2), carcass characteristics (hot carcass weight, longissimus muscle area, backfat thickness, marbling score, and YG; $P > 0.12$; Table 2), or carcass quality ($P > 0.19$). Kidney, pelvic, and heart fat tended to be higher ($P = 0.06$; Table 2) for control and high-Se wheat steers compared with sodium selenate and high-Se hay.

Per unit of tissue, high-Se wheat resulted in the greatest amount of Se being distributed to all tissues sampled. As we expected, steers receiving control diets, with adequate dietary Se, exhibited the lowest concentration of tissue Se (Table 3). Kidney, spleen, and hair Se concentration was the greatest in high-Se wheat followed by high-Se hay, sodium selenate, and control treatments ($P < 0.01$; Table 3). Selenium concentration in the liver was the highest ($P = 0.003$) in high-Se wheat and sodium selenate steers, but in the semitendinosus muscle, sodium selenate and control steers had the lowest ($P < 0.01$; Table 3) Se concentration. Kidney, liver, and spleen weights did not differ ($P < 0.53$; Table 3) between treatments; therefore, similar differences in total organ Se content, as observed for Se concentration per unit of tissue, would be expected.

Discussion

Some plant species are capable of accumulating Se to a greater extent than other plants, and are thus referred to as *accumulator species* (Rosenfeld and Beath, 1964). Species that do not accumulate Se are reported (Olson et al., 1970; Djujic et al., 2000) to contain selenomethionine as the main molecular form of Se. Other forms of selenium commonly found are Se-methylselenocysteine and selenocysteine. Grasses have been reported to contain several different molecular forms of Se, including Se-methylselenocysteine, selenomethionine, and selenocysteine (Wu et al., 1997). Bañuelos and Mayland (2000) identified and further quantified selenocysteine, selenomethionine, Se-methylselenocysteine, and selenocystine to be present in Se-enriched canola leaves (approximately 4 ppm total Se, DM basis). Interestingly, the concentrations of these four amino acids were 28, 110, 81, and 37 ppm (DM basis), respectively. Based on these data, we speculate that the predominate form of Se found in the feedstuffs we used was most likely selenomethionine; however, we realize that Se distribution among different molecular forms can vary. Ammerman and Miller (1975) reported a higher bioavailability of water-soluble and organically bound forms of Se for plants and animals. Beilstein and Whanger (1986) demonstrated that selenomethionine had a higher bioavailability than inorganic Se. Furthermore, Combs and Combs (1986) concluded that increased absorption and storage of selenomethionine vs. sodium selenite are due to the direct incorporation of selenomethionine into the proteins. Interestingly, Ammerman and Miller (1975) reported the water-soluble and organically bound forms of Se to be the least toxic form of the element when provided in excess. Further demonstrated in the study of Hurlbut and Martin (1972), mice fed inorganic Se showed more toxic symptoms compared with those consuming organically bound Se.

Performance measures, carcass characteristics, and carcass quality of the steers in the current study were not affected by dietary concentration or source of Se.

Table 3. Organ weights and tissue Se distribution in finishing steers fed diets (126 d at 2.38% BW, DM basis) containing either adequate (CON) Se or high Se provided in the form of sodium selenate (SEO), alfalfa/grass hay (HAY), or wheat (WHT)

	Treatment					
Item	CON	SEO	HAY	WHT	SE	*P*-value[a]
Kidney						
Weight, g	1,166	1,161	1,131	1,148	40	0.93
Weight, g/kg HCW[b]	3.33	3.47	3.43	3.39	0.13	0.83
Se, ppm[c]	8.40[d]	10.05[e]	10.86[f]	12.89[g]	0.26	<0.001
Liver						
Weight, g	6,693	6,752	6,842	7,141	237	0.53
Weight, g/kg HCW[b]	19.97	20.08	21.15	21.02	0.58	0.24
Se, ppm[c]	2.33[d]	9.91[e]	6.56[f]	10.79[g]	0.80	0.003
Spleen						
Weight, g	1,100	1,042	1,091	1,057	53	0.84
Weight, g/kg HCW[b]	3.29	3.05	3.23	3.13	0.22	0.77
Se, ppm[c]	2.00[d]	2.60[e]	3.82[f]	5.16[g]	0.09	<0.001
Semitendinosus muscle						
Se, ppm[c]	1.33[d]	1.55[d]	3.32[e]	4.41[f]	0.18	<0.001
Hair						
Se, ppm[c]	1.80[d]	4.00[e]	5.93[f]	10.54[g]	0.56	<0.001

[a]All pairwise comparisons (least significant difference; significant if $P < 0.05$). Number of steers associated with treatments were CON, n = 11; SEO, n = 12; HAY, n = 11; and WHT, n = 9.
[b]HCW = hot carcass weight.
[c]Expressed on a DM basis.
[d,e,f,g]Means within a row with different superscripts differ.

Similarly, Hintze et al. (2002) reported no differences in performance (feed intake, ADG, and final body weight) between steers finished (105 d) on either 0.62 or 11.9 mg Se/kg of diet as high-Se hay and wheat mix. Taken together, these studies clearly indicate that, when provided as an organically bound source (e.g., high-Se wheat, or alfalfa/grass hay), supranutritional Se levels do not negatively affect performance of finishing beef steers. To date, no data are available describing the effects of supranutritional dietary Se on finishing beef steers except for the study of Hintze et al. (2002) and the study reported herein. Van Ryssen et al. (1989) fed mature ewes high-Se wheat at 1 mg of Se/kg diet and found liver, wool, and muscle to have the greater Se concentrations compared with sheep supplemented with a similar quantity of sodium selenite. In an investigation with swine, Kim and Mahan (2001) reported that ADG, feed intake, and final BW decreased with increasing inclusion of dietary Se from 5 to 20 ppm. Uniquely, this effect was more pronounced when Se was provided as sodium selenite vs. Se-enriched yeast, an organically bound source, which would agree with the data of Ammerman and Miller (1975) discussed above. Although fed at much lower concentrations, Mahan et al. (1999) found no differences in the carcass characteristics of swine fed either sodium selenite or Se-enriched yeast (Se = 0.05, 0.1, 0.2, or 0.3 ppm). Likewise, Beilstein and Whanger (1988) reported no difference in weight gain of rats consuming 0.2 ppm Se fed as either sodium selenite or selenomethionine.

Independently, the dietary concentration (Bañuelos and Mayland, 2000) and molecular form (Panter et al., 1996) of Se affects the distribution of Se throughout the body. In a unique study using Se-enriched canola, Bañuelos and Mayland (2000) observed increased Se in the kidney, liver, and spleen of lambs consuming 1.94 to 3.63 ppm Se vs. 0.38 to 0.56 ppm Se. However, when dietary Se concentration was similar between treatments (i.e., approximately 25 ppm; Panter et al., 1996), Se distribution in the liver, kidney, and spleen of swine was greater when Se was fed as seleno-DL-methionine vs. sodium selenate or *Astragalus bisulcatus*. Likewise, hair Se concentration of first-parity gilts was increased when Se-enriched yeast was the Se supplement source as opposed to sodium selenite provided at 0.3, 3, 7, and 10 ppm (Kim and Mahan, 2001). We observed that steers consuming high-Se wheat had greater Se concentrations in all tissues, except liver, compared with steers consuming sodium selenate at a similar Se concentration. Steers fed sodium selenate had higher Se concentrations in the liver than those fed high-Se grass/alfalfa hay. This was surprising to us because hay is an organically bound source of Se, and, therefore, the distribution of Se should follow a pattern similar to the one observed in the steers treated with high-Se wheat. The lack of similarity could be due to the varying molecular forms of Se present in forages vs. grains (Wu et al., 1997; Djujic et al., 2000; Bañuelos and Mayland, 2000). Our results regarding tissue Se concentrations are similar to data summarized by Combs and Combs (1986), which indicate that Se concentrations usually rank the highest in the kidney, intermediate in liver, and least in skeletal muscle (Combs and Combs, 1986).

Based on the evidence presented herein, finishing steers fed feedstuffs naturally high in Se, especially wheat grain, have substantially increased Se concentration in the semitendinosus muscle. Ehlig et al. (1967) compared selenite and selenomethionine (0.4 mg Se/d) and found that selenomethionine resulted in higher amounts of Se in lamb tissues, especially muscle. Furthermore, Allaway (1973) and van Ryssen et al. (1989) reported greater incorporation of Se in skeletal muscle of lambs consuming up to 1.0 ppm Se as an organically bound Se source vs. sodium selenite. In swine, Se-enriched yeast resulted in more Se in the loin compared with sodium selenite (dietary Se = 0.1 to 20 ppm; Mahan and Parrett, 1996; Kim and Mahan, 2001). Our data indicate that sodium selenate does not increase Se concentration the skeletal muscle of steers.

As previously mentioned, North Americans acquire the majority of their daily Se requirement from wheat grain and beef (Schubert et al., 1987; Holden et al., 1991; Hintze et al., 2001). A 100-g portion of average beef round (fresh basis; USDA, 2003) provides 24.8 μg of Se, which is approximately 45% and 35% of the recommended dietary allowance (RDA, 1989) of Se for middle-aged human females (55 μg) and males (70 μg), respectively. Comparatively, a 100-g portion of the semitendinosus muscle from steers fed high-Se wheat would provide approximately 146 μg of Se, approximately 265% and 209% of the Se RDA for middle-aged human females and males, respectively. Shi and Spallholz (1994) found that Se fed to rats in the form of beef was more bioavailable than Se fed as sodium selenite or selenate, a traditional form of Se supplementation in humans. As such, "high-Se" beef seems to be a potential source for Se supplementation.

Implications

The inclusion of high-selenium wheat or hay, providing approximately ninefold more than the NRC selenium requirement, in a beef finishing diet enhances the distribution of selenium in edible muscle without compromising animal performance or final product quality. Furthermore, high-selenium wheat results in greater selenium status, as indicated by kidney, liver, muscle, and spleen selenium concentrations, compared with a traditional form of selenium supplement, sodium selenate. These results reveal a potential market for naturally high-selenium feedstuffs through the provision of a readily available selenium source for cattle and an effective method to create a beef product that is naturally high in selenium.

Literature Cited

Allaway, W. H. 1973. Selenium in the food chain. Cornell Vet. 63(Suppl. 3):151–170.

Ammerman, C. B., and S. M. Miller. 1975. Selenium in ruminant nutrition: A review. J. Dairy Sci. 58:1561–1577.

Bañuelos, G. S., and H. F. Mayland. 2000. Absorption and distribution of selenium in animals consuming canola grown for selenium phytoremediation. Ecotoxicol. Environ. Saf. 46:322–328.

Beilstein, M. A., and P. D. Whanger. 1988. Glutathione peroxidase activity and chemical forms of selenium in tissues of rats given selenite or selenomethionine. J. Inorg. Biochem. 33:31–46.

Beilstein, M. A., and P. D. Whanger. 1986. Deposition of dietary organic and inorganic selenium in rat erythrocyte proteins. J. Nutr. 116:1701–1710.

Clark, L. C., G. F. Combs, Jr., B. W. Turnbull, E. H. Slate, D. K. Chalker, J. Chow, L. S. Davis, R. A. Glover, G. F. Graham, E. G. Gross, A. Krongard, J. L. Lesher, Jr., H. K. Park, B. B. Sanders, C. L. Smith, and J. R. Taylor. 1996. Effect of selenium supplementation for cancer prevention in patients with carcinoma of the skin. JAMA (J. Am. Med. Assoc.) 276:1957–1962.

Combs, G. F., Jr., and S. B. Combs. 1986. The Role of Selenium in Nutrition. Academic Press, Orlando, Florida.

Djujic, I. S., O. N. Jozanov-Stankov, M. Milovac, V. Jankovic, and V. Djermanovic. 2000. Bioavailability and possible benefits of wheat intake naturally enriched with selenium and its products. Biol. Trace Elem. Res. 77:273–285.

Ehlig, C. F., D. E. Hogue, W. H. Allaway, and D. J. Hamm. 1967. Fate of selenium from selenite or selenomethionine with or without vitamin E in lambs. J. Nutr. 92:121–126.

FDA. 2003. Code of Federal Regulations: Title 21, Food and Drugs. Available: http://www.access.gpo.gov/cgi-bin/cfrassemble.cgi?title=200321. Accessed Sept. 9, 2003.

Finley, J. W., C. D. Davis, and Y. Feng. 2000. Selenium from high selenium broccoli protects rats from colon cancer. J. Nutr. 130:2384–2389.

Finley, J. W., L. Matthys, T. Shuler, and E. Korynta. 1996. Selenium content of foods purchased in North Dakota. Nutr. Res. 16:723–728.

Hintze, K. J., G. P. Lardy, M. J. Marchello, and J. W. Finley. 2001. Areas with high concentrations of selenium in the soil and forage produce beef with enhanced concentrations of selenium. J. Agric. Food Chem. 49:1062–1067.

Hintze, K. J., G. P. Lardy, M. J. Marchello, and J. W. Finley. 2002. Selenium accumulation in beef: Effect of dietary selenium and geographical area of animal origin. J. Agric. Food Chem. 50:3938–3942.

Holden, J. M., S. Gebhardt, C. S. Davis, and D. G. Lurie. 1991. A nationwide study of the selenium contents and variability of white bread. J. Food Compos. Anal. 4:183–195.

Hurlbut, J. A., and J. L. Martin. 1972. Biochemical and toxicological responses of mice fed selenomethionine, Se-methylselenocysteine, or sodium selenite. Fed. Proc. 31:692. (Abstr.)

Kim, Y. Y., and D. C. Mahan. 2001. Comparative effects of high dietary levels of organic and inorganic selenium on selenium toxicity of growing-finishing pigs. J. Anim. Sci. 79:942–948.

Mahan, D. C., T. R. Cline, and B. Richert. 1999. Effects of dietary levels of selenium-enriched yeast and sodium selenite as selenium sources fed to growing-finishing pigs on performance, tissue selenium, serum glutathione peroxidase activity, carcass characteristics, and loin quality. J. Anim. Sci. 77:2172–2179.

Mahan, D. C., and N. A. Parrett. 1996. Evaluating the efficacy of selenium enriched yeast and sodium selenite on tissue selenium retention and serum glutathione peroxidase activity in grower and finisher swine. J. Anim. Sci. 74:2967–2974.

NRC. 1996. Pages 113–171 in Nutrient Requirements of Beef Cattle. 7th rev. ed. Natl. Acad. Press, Washington, DC.

Olson, O. E., E. J. Novacek, E. I. Whitehead, and I. S. Palmer. 1970. Investigation on selenium in wheat. Photochemistry 9:1181.

Panter, K. E., W. J. Hartley, L. F. James, H. F. Mayland, B. L. Stegelmeier, and P. O. Kechele. 1996. Comparative toxicity of selenium from seleno-DL-methionine, sodium selenate, and *Astragalus bisulcatus* in pigs. Fundam. Appl. Toxicol. 32:217–223.

RDA. 1989. Pages 217–222 in Recommended Dietary Allowances. 10th rev. ed. Natl. Acad. Press, Washington, DC.

Rosenfeld, I., and O. A. Beath. 1964. Selenium Geobotany, Biochemistry, Toxicity, and Nutrition. Academic Press, New York.

Schubert, A., J. M. Holden, and W. R. Wolf. 1987. Selenium content of a core group of foods based on a critical evaluation of published analytical data. J. Am. Diet. Assoc. 87:285–299.

Shi, B., and J. E. Spallholz. 1994. Selenium from beef is highly bioavailable as assessed by liver glutathione peroxidase activity (EC 1.11.1.9) and tissue selenium. Br. J. Nutr. 72:873–881.

USDA. 2003. National Nutrient Database: Standard Reference 16, No. 13868. Available: http://www.nal.usda.gov/fnic/foodcomp/Data/SR16/reports/sr16fg13.pdf. Accessed Sept. 9, 2003.

Van Ryssen, J. B. J., J. T. Deagen, M. A. Beilstein, and P. D. Whanger. 1989. Comparative metabolism of organic and inorganic selenium by sheep. J. Agric. Food Chem. 37:1358–1363.

Whanger, P. D., C. Ip, C. E. Polan, P. C. Uden, and G. Welbaum. 2000. Tumorigenesis, metabolism, speciation, bioavailability, and tissue deposition of selenium in selenium-enriched ramps (*Allium tricoccum*). J. Agric. Food Chem. 48:5723–5730.

Wu, L., X. Guo, and G. S. Bañuelos. 1997. Accumulation of seleno-amino acids in legume and grass plant species grown in selenium-laden soils. Environ. Toxicol. Chem. 16:491–497.